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TWO DIMENSIONAL RECURSIVE ESTIMATION WITH APPLICATION TO REAL-T--ETC(U)
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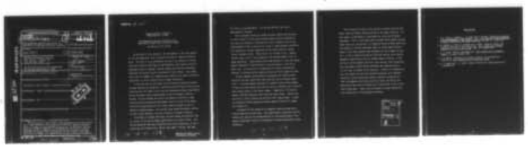

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LEVEL

1. REPORT NUMBER: AFOSR-TR-78-1407 / 2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle): TWO DIMENSIONAL RECURSIVE ESTIMATION WITH APPLICATION TO REAL-TIME FILTERING OF IMAGES.	5. TYPE OF REPORT & PERIOD COVERED: Interim
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): John W./Woods	8. CONTRACT OR GRANT NUMBER(s): AFOSR-77-3361
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Rensselaer Polytechnic Institute, Dept. of Elec. & Systems Eng., Troy, New York 12181	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 61102F 2304/A6
11. CONTROLLING OFFICE NAME AND ADDRESS: Air Force Office of Scientific Research/NM, Bolling AFB, Washington, DC 20332	12. REPORT DATE: 1978
	13. NUMBER OF PAGES: 4
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): Interim rept. 1 Jul 77-31 Jul 78,	15. SECURITY CLASS. (of this report): UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report) 31 Jul 78

Approved for public release; distribution unlimited.

D D C

NOV 1 1978

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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The main goal of this program is the development of efficient methods for the two-dimensional (2-D), recursive filtering of images corrupted by noise. This goal is to be achieved by the use of our extension of Kalman recursive estimation techniques to two-dimensions, which permits order-of-magnitude savings in computer time and storage over previously developed techniques for optimal recursive estimation of noisy images. Such images could arise for example in a communications context by an image transmission system which is noise limited because of power constraints.

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AFOSR-TR- 78-1407

Interim Scientific Report on
AFOSR Grant No. 77-3361

Two Dimensional Recursive Estimation With
Application to Real-Time Filtering of Images

for period 7/1/77-7/31/78

The main goal of this program is the development of efficient methods for the two-dimensional (2-D), recursive filtering of images corrupted by noise. This goal is to be achieved by the use of our extension of Kalman recursive estimation techniques to two-dimensions, which permits order-of-magnitude savings in computer time and storage over previously developed techniques for optimal recursive estimation of noisy images. Such images could arise for example in a communications context by an image transmission system which is noise limited because of power constraints.

In the first year of this grant, the 2-D recursive estimation method has been improved by substantially increasing the efficiency of the existing algorithm both with regard to run time and random-access memory requirements. We have achieved a better understanding of the 2-D boundary condition problem. We have extended the recursive estimation algorithm to image restoration and have obtained experimental results to confirm the theory. Also we have experimented with 2-D linear predictive models as well as spectrally designed models. We find the linear predictive models, derived by least squares methods, to be well suited to 2-D Kalman filtering.

With regard to program efficiency, we have reduced the execution time by a factor of two and the memory page-minutes by a factor of four. Also we have decoupled covariance processing from picture processing, so that a picture may be filtered with a (2x2)th order model in 45 sec. CPU time.

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The time is on the IBM 360/67. For the new IBM 3033, the time is approximately 4 seconds.

The 2-D boundary condition problem has been studied from the point of view of causal (in the raster scanning sense) recursive estimation. This work has resulted in an extension of the 2-D Kalman filter to the reduced update filter in the realistic case of random boundary conditions. This essentially involves augmenting the 2-D state vector to include 'future' boundary values. These results are included in [5]. However the main topic of [5] is the extension of the reduced update filter to image restoration. These deconvolution type problems fit into the reduced update formulation if the distortion or blurring matrix is FIR and of small size. This assumption is appropriate for several deconvolution problems, including blurring caused by motion and finite apperture width.

We have compared various modeling procedures with regard to both subjective and mean square error when used with the 2-D reduced update filter. The three methods consisted of a spectral design using windows, a linear prediction design using the 2-D Fourier transform, and a recursive least squares design in the spatial domain. Comparison of the results showed a 20% MSE advantage to the recursive least squares. Subjectively the results slightly favored the recursive-least squares model. A paper on the spectral design method and reduced update filtering will appear this October [3].

A problem with the optimality of dynamical prediction when doing reduced updating has been noted. This necessitated a correction item [4] pointing out weak but not strong optimality of the reduced update filter. However experimental results are presented to indicate approximate strong optimality.

The 2-D recursive theory allows spatially varying recursive data models that would permit better matching of the image statistics. We have begun to experimentally investigate this using two different approaches: first, a multi-mode recursive model which matches varying image statistics; and second, a 2-D adaptive recursive model which uses the concepts of the well developed theory of system identification. Papers on the later approach were presented this past summer [1] and [2]. In [2] an adaptive estimation algorithm combines least squares parameter identification with 2-D reduced update filtering. A comparison of infinite memory recursive least squares, block processing, and fixed memory identification procedures was conducted using a (1x1)th order 2-D Kalman filter structure. Factors of 2 reduction in mse, with respect to spatially constant processing, with improved subjective picture quality were noted using block processing on a (5x5) non-symmetric half-plane type data history consisting of 41 points which were used to estimate the 5 coefficients in the (1x1)th order Kalman model. Under study are methods to remove observation noise induced bias in the parameter estimates.

Publications

1. V. K. Ingle, A. Radpour, J. W. Woods and H. Kaufman, "Recursive Estimation with Non-Homogeneous Signal Models", Proc. IEEE Computer Society Conference on Pattern Recognition and Image Processing, Chicago, IL , June 1978.

2. A. Radpour, V. Ingle, H. Kaufman and J. Woods, "Adaptive Kalman Type Estimation Applied to Image Processing", Proc. Twenty-First Midwest Symposium on Circuits and Systems, Ames, IO , August 1978.

3. J. W. Woods, "Markov Image Modeling", IEEE Transactions on Automatic Control, to appear October 1978.

4. J. W. Woods, "Correction to 'Kalman Filtering in Two-Dimensions'", submitted to IEEE Transactions on Information Theory.

5. J. W. Woods and V. K. Ingle, "Kalman Filtering for Image Restoration", in preparation.